Short isthmic versus long trans-isthmic C2 screw: anatomical and biomechanical evaluation

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Abstract

Introduction The Harms technique is now considered as the gold standard to stabilize C1–C2 cervical spine. It has been reported to decrease the risk of vertebral artery injury. However, the risk of vascular injury does not totally disappear, particularly due to the proximity of the trans-isthmic C2 screw with the foramen transversarium of C2. In order to decrease this risk of vertebral artery injury, it has been proposed to use a shorter screw which stops before the foramen transversarium.

Object The main objective was to compare the pull-out strength of long trans-isthmic screw (LS) versus short isthmic screw (SS) C2 screw. An additional morphological study was also performed.

Method Thirteen fresh-frozen human cadaveric cervical spines were included in the study. Orientation, width and height of the isthmus of C2 were measured on CT scan. Then, 3.5-mm titanium screws were inserted in C2 isthmus according to the Harms technique. Each specimen received a LS and a SS. The side and the order of placement were determined with a randomization table. Pull-out strengths and stiffness were evaluated with a testing machine, and paired samples were compared using Wilcoxon signed-rank test and also the Kaplan–Meier method.

Results The mean isthmus transversal orientation was $20° \pm 6°$. The mean width of C2 isthmus was less than 3.5 mm in 35 % of the cases. The mean pull-out strength for LS was 340 ± 85 versus 213 ± 104 N for SS ($p = 0.004$). The mean stiffness for the LS was 144 ± 40 and 97 ± 54 N/mm for the SS ($p = 0.02$).

Discussion The pull-out strength of trans-isthmic C2 screws was significantly higher (60 % additional pull-out resistance) than SSs. Although associated with an inferior resistance, SSs may be used in case of narrow isthmus which contraindicates 3.5-mm screw insertion but does not represent the first option for C2 instrumentation.

Level of evidence Level V.

Keywords Biomechanics · Biomechanical testing · C2 pedicular screw · Isthmic screw · Cadaveric study

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Introduction

C1–C2 posterior fixation is usually required when a destabilizing pathology occurs in the upper cervical spine area: spine injury, tumour, degenerative conditions and inflammatory illness. The main objective of the surgery is then to reduce abnormal displacement and to ensure stability by obtaining a solid intervertebral fusion. It has been shown that intervertebral fusion was best achieved when the instrumentation succeeds to minimized motion [1]. In order to perform an efficient C1–C2 stabilization, numerous techniques have been developed and reported in the literature, including cable and graft fixation (Brooks, Gallie) [2] alone or associated with screw fixation, hook and/or screw fixation [3–5].

In the normal population, the C1–C2 joint is characterized by a wide range of motion in flexion/extension (about 20°) and particularly in axial rotation (about 60°), representing approximately 50 % of the entire cervical spine mobility in axial rotation [6].

Regardless of the aetiology, C1–C2 instability is characterized by a significantly greater translational and rotational range of motion than the normal conditions [7, 8]. Effective control of this C1–C2 hypermobility represents the challenge of spinal fixation devices. Further to cables and hooks, and in order to increase segmental stability and consequently improve fusion rates, screw fixation techniques have been more recently introduced: Gallie or Brooks fusion techniques combined with one or two Magerl's screws [2] (i.e. C1–C2 transarticular screws), Magerl's [3, 4] screws alone, Harms' [5] construct (i.e. C1 lateral mass screw and C2 isthmic screws), laminar screws [9] and various combinations of several screw–rod–wiring techniques.

In 1988, Goel and Laheri [10] described the C1 lateral mass screw and C2 pedicle screw fixation which was then popularized by Harms and Melcher [5] in 2001. In this technique, the so-called Harms technique, two poly-axial screws are inserted into the C1 lateral mass and C2 pedicle on both sides and then locked together with two titanium rods.

Compared to Magerl's technique with C1–C2 trans-articular screw, the Harms technique has been reported to decrease the risk of vertebral artery (VA) injury [11] and also to avoid the requirement of pre-/peroperative reduction manoeuvre. However, the risk of vascular injury does not totally disappear, particularly due to the proximity of the trans-isthmic C2 screw with the foramen transversarium of C2. In a recent meta-analysis by Elliott et al. [12], this risk of VA injury was estimated to 2 % (IC: 1.1–3.4).

In order to decrease the risk of VA injury associated with the placement of C2 pedicle screw, it has been proposed to use a shorter screw [13], so-called short isthmic C2 screw, which stops in regard to the foramen transversarium. However, although short C2 screw could be an attractive option from an anatomical point of view, the biomechanical relevance of this modified Harms' technique remains unclear, particularly with regard to the short isthmic screw pull-out strength.

The main objective of this study was thus to compare the pull-out strength of long trans-isthmic screw (LS for long screw) versus short isthmic (SS for short screw) C2 screw. We hypothesized that pull-out strength was higher for trans-isthmic screw than for short isthmic screw.

A quantitative morphological study, based on CT scan, was also performed in order to establish the anatomical relationship among the vertebral foramen, the isthmus and the spinal canal. Dimensions of C2 isthmus were also determined.

Materials and methods

Specimen's preparation

Thirteen fresh-frozen human cadaveric cervical spines were obtained from the Anatomical Laboratory of the University Hospital. The tissue donors or their legal guardians provided informed written consent. Immediately after dissection, spinal segments were sealed in biohazard bags and stored at −20 °C. All of them were evaluated for vertebral defects, trauma or spontaneous C1–C2 arthrodesis. Then the C2 vertebra was extracted from the anatomical specimen. All specimens were sealed in triple biohazard bags, and a three-dimensional CT scan was then realized. The day prior to the biomechanical test, the spinal segments were put at +6 °C for 12 h and then for 2 h at 20 °C in order to defrost.

CT scan protocol

The CT bone acquisition protocol consisted of 1.25-mm axial sections with 0.625 mm spacing, 12 kV, 350 mA (General Electric-Optima CT660-GE Healthcare). For all measurements, the isthmus plane was chosen as the reference axial section (Fig. 1).

Using the 3D CT scan, isthmus widths, lengths and orientations were measured in the reference axial plane (Fig. 2).

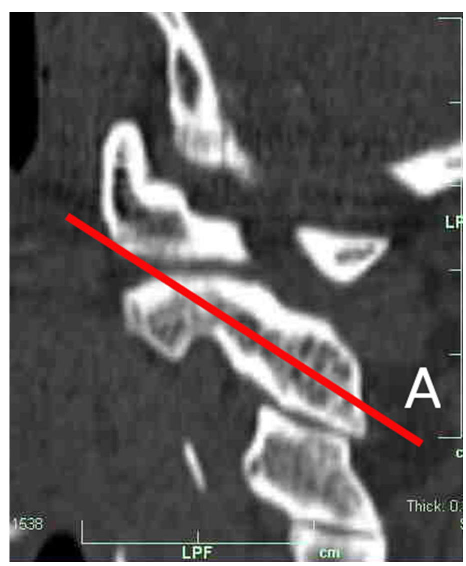


Fig. 1 Reference axial plane (*A*)

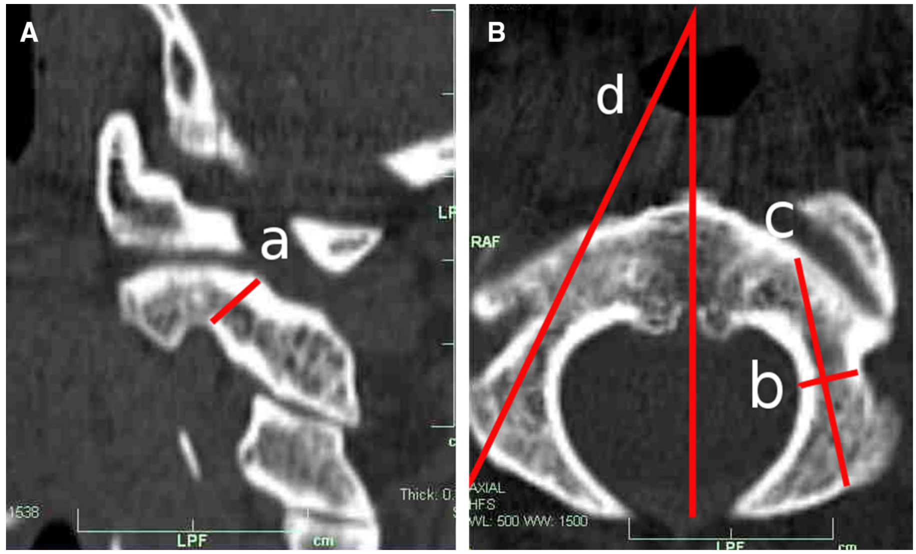


Fig. 2 3D CT scan: measure of isthmus height (*a*), width (*b*), length (*c*) and orientation (*d*)

Screws insertion

Screws were inserted under view control according to the Harms [5] technique. The medial wall of C2's isthmus was delineated with a thin spatula placed into the canal in contact with the medial wall. The posterior surface of C2's articular facet was divided into 4 parts, and the entry point was located at the medial and cranial quadrant of this area at the junction between the lamina and the facet. A pilot hole was done with a 2.5-mm burr. Then a 3-mm drilling was conducted with approximately 20°–30° in both convergent and cephalic directions. Due to anatomical variations, the drilling direction was adapted to the orientation of the superior and medial surface of C2's isthmus.

Screws' characteristics

Specific screw design was elaborated for this study (Scient'x-Alphatec Carlsbad, USA). The screw had an external diameter of 3.5 mm, and they were made in titanium and presented 24 mm of cortico-spongious thread. To improve the grip in the testing machine, the screws were prolonged with an 80-mm-long unthreaded portion.

The screws' insertion length was determined according to CT scan data: in the case of a short isthmic screw, the length was inserted so as to reach the isthmus; in the case of trans-isthmic screw, the entire portion of cortico-spongious thread was inserted (24 mm). The cortical bone was checked to exclude cortical breach. After screw insertion, anatomical specimens were frozen at −20 °C.

The side, the type and order of screws placement were randomized.

Biomechanical tests

After defrosting the spinal specimen, a silicon spray was applied on the vertebra and on the screws in order to limit the friction during the tensile test. A plastic cylinder of 5 mm diameter and of 10 mm length was then inserted on each screw. An epoxy resin cast was prepared and applied around the plastic cylinder, between the posterior surface of the vertebra and the cylindrical spacer, in order to apply a pure axial force along the screw's axis. After polymerization, the vertebra was placed under a special frame (based on the protocol reported by Lill et al. [14] study) and the screw was gripped to the testing machine (Instron 8802, High Wycombe, England) (Fig. 3) in order to

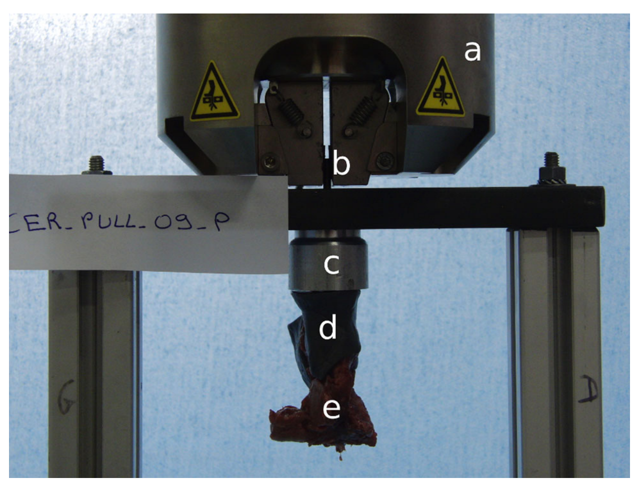


Fig. 3 Experimental device during pull-out testing (*a* testing machine, *b* non-threaded screw, *c* metal cylinder, *d* resin cast, *e* C2 vertebra)

complete the tensile test. The load cell (1 KN, accuracy 0.5 %) was located at the inferior part of the testing machine.

The test was done with a constant pull-out speed of 6 mm/mn, a preload of 40 N and a frequency of acquisition of 1 Hz. The acquisition was done until the screw was completely pulled out. The order of tensile test (SS or LS first) was randomized.

Data analysis

Maximal pull-out strength was defined as the maximal load of the load–displacement curve, and stiffness was defined as the slope of the linear part of the load–displacement curve (Fig. 4). Regarding the stiffness, two distant points between the lag and yield point were thus selected on the linear part of the load–displacement curve permitting to obtain the value of the slope using linear regression method with R 2.14.2 (R: A Language and Environment for Statistical Computing, R Core Team, R Foundation for Statistical Computing, Vienna, Austria, 2013).

Statistical analysis

Statistical analysis was done with R 2.14.2. Statistical significance was measured at the level $\alpha < 0.05$ for all statistical analyses. Morphological data were described with mean, standard error, min and max. The pull-out strength and stiffness between long and short pedicle screws were compared using Wilcoxon signed-rank test and also the Kaplan–Meier method.

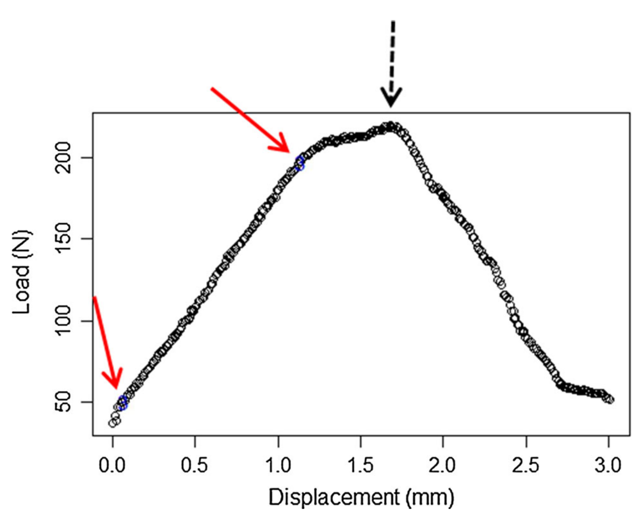


Fig. 4 *Load displacement curve* selection of two points of the linear part of the curve (*red arrow*), *dot arrow* maximal pull-out strength

Results

Anatomical study

The mean width of the isthmus was 3.5 ± 1 mm [2–5], and its mean height was 10 ± 2 mm [5–12]. The mean convergent angle was 20° ± 6° [10–29]. There was no significant difference between the left and right isthmus.

The mean length of the pedicle was, respectively, 23.6 ± 2.3 mm [20–27] and 24.9 ± 2.3 mm [21–28] for the left and right pedicle. There was no significant difference between these values. The mean length of short screws was 10.9 ± 1.8 mm [8–14] for the left side and 12 ± 1.6 mm [9–14] for the right.

Biomechanical tests

Four specimens were excluded from the analysis because of resin breakage in three cases and a case of screw slide during the test.

Pull-out resistance and stiffness

Mean values and standard deviation of the maximum pull-out strength and stiffness are summarized in Table 1 for two surgical techniques. The difference between long screw (LS) and short screw (SS) pull-out strength was statistically significant ($p = 0.004$). On average, more than 120 N difference between two types of screws was observed, corresponding to a mean gain of 60 % additional pull-out resistance for the LS cases. The stiffness provided by LS was significantly stiffer than for SS ($p = 0.02$).

Survival rate (according to Kaplan–Meier) of long and short isthmic screws: Regarding the survival rate of the screws according to Kaplan–Meier estimation, a significant difference between two curves was observed ($p = 0.02$) (Fig. 5).

Correlation between Hounsfield unit and maximum pull-out strength: no correlation was found between bone density (as estimated by Hounsfield unit, measured on the CT scan) and long pedicle screw pull-out strength ($\rho = 0.05$, $p = 0.9$) and short screws ($\rho = 0.6$, $p = 0.1$).

Table 1 Mean pull-out strength and stiffness

	LS ($n = 9$)	SS ($n = 9$)
Pull-out strength	340 ± 85 N	213 ± 104 N
Stiffness	144 ± 40 N/mm	97 ± 54 N/mm

LS long screws, *SS* short screws

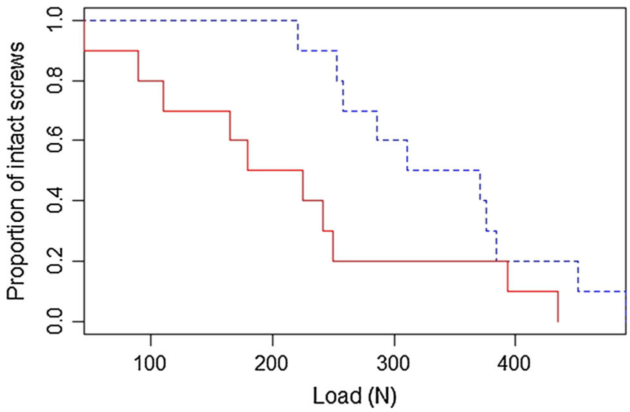


Fig. 5 Kaplan–Meier estimate curve ($p = 0.02$) (*continue line* SC, *dotted line* LS)

Discussion

Anatomical part

The suitability of the C2 isthmus for screw has been described in several studies. Two parameters appear to be essential in this respect: the course of the vertebral artery and the isthmus' morphology.

As the cranio-vertebral junction surgery presents a risk of vertebral artery injury, many authors [15, 16] reported the anatomical variation of this artery. Cacciola et al. [15], through an anatomical study, reported that the distance of the dome of the loop of the vertebral artery to the superior articular facet ranged from 0.6 to 4.8 mm. Paramore et al. [16] found that 20 % of their reported cases had a high vertebral groove. In these cases, the isthmus was not suitable for a 3.5-mm screw. This point was confirmed by Bhatnagar et al. [17] who reported that 24 % of C2 pedicles were not suitable for a 3.5-mm screw.

Concerning the convergence, height, length and width of the pedicle of C2, many authors [18, 19] reported anatomical or computed tomographic studies (see Table 2). Regarding the convergence of the pedicle, Kazan et al. reported 24.6° and 23.2°, Harms et al. reported 20°–30°, whereas Smith et al. [19] reported 43.9°. In our study, the mean convergence was 20°. It was less than 20° in 5/26 cases (19 %) and more than 30° in 5/26 cases (19 %).

Concerning the pedicle width, the mean value was 3.5 mm in our study. It was less than the previous studies. In our point of view, the CT scan reference plane for measuring pedicle width and convergence could explain these differences.

Regarding the vascular risk, several studies reported that 25 % of patients have an aberrant vertebral artery which cannot permit a safe screw insertion [12].

Thus, screw–rod fixation according to Harms technique is now accepted as an alternative to C1–C2 trans-articular screw fixation when C1–C2 stabilization is required. However, C2 pedicle screw placement remains risky which concerns the vertebral artery. A shorter isthmic C2 screw, attending short to the beginning of the isthmus, could reduce significantly the risk of vertebral artery injury.

Biomechanical part

Regarding the protocol of biomechanical tests, it has been showed that the screw pull-out strength was influenced by the screw insertion method, the bone density and the specimen fixation method [20]. In order to limit these biases, each specimen received two types of screws which were inserted by the same operator, according to a randomization table defining the side, order of insertion and order of pull-out test. Furthermore, the statistical analysis was carried out using paired tests.

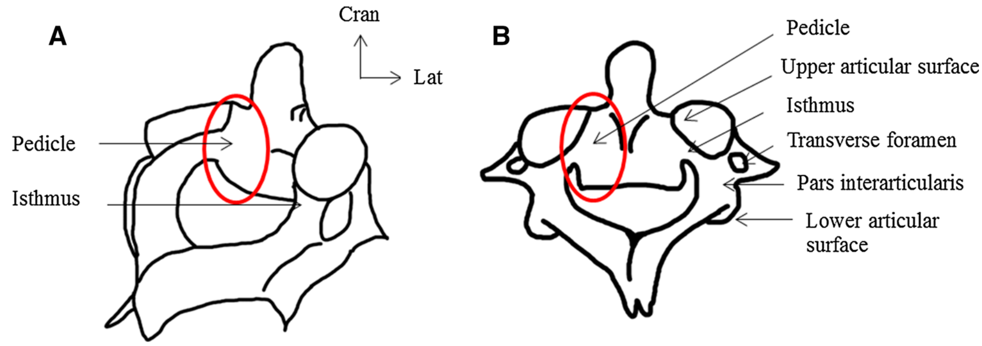
The experimental protocol was based on the work by Lill et al. [14]. This protocol allowed for a precise controlling of the loading direction, which resulted in a pure tensile loading along the screw's axis, thus minimizing undesirable force and parasite moments. In our study, the use of the epoxy resin permits to distribute homogeneously the contact stresses on a large surface along the posterior arch, thus limiting possible local stresses concentration at the bone–screw interface. Although the fixation device had been designed in order to decrease the influence of the fixation method, three specimens were excluded from the study because of resin breakage.

Dmitriev et al. [21] compared pull-out strength of C2 trans-isthmic screws to pars screws after cyclic axial loading (2000 cycles, 50 N, 1 Hz). Lehman et al. [22] also compared pull-out strength of trans-isthmic C2 screws to

Table 2 Literature synthesis concerning C2 pedicle measurement

References	Specimens	Convergence (SD)	Pedicle width (SD)
Kazan et al. [18]	40	R: 24.6° (3.54)	R: 8.3 mm (1.64)
		L: 23.2° (3.8)	L: 7.9 mm (1.59)
Bhatnagar et al. [17]	50		4.7 mm (1.7)
Resnick et al. [20]	60		5.3 mm (1.4)
Smith et al. [19]	93	43.9° (3.9)	5.8 mm (1.2)
Present study	13	20° (6)	3.5 mm (1)

Fig. 6 Anatomical localization of the pars interarticularis and the pedicle (*red ring*) of C2 (**a** postero-lateral view, **b** posterior view)



pars screws. In these two studies, the short screws placement is unclear: Lehman and Dmitriev deal with "pars screws" which seem to be different from short isthmic screws. So, as far as we know, there is no study in the literature comparing the bone anchorage of short and long isthmic screws.

Further to this comment, it has to be noticed that the anatomical terminology concerning the pedicle of C2 is unclear in the literature. The pars interarticularis corresponds to the segment located between two (upper and lower) articular surfaces (Fig. 6). The pedicle is the part of the vertebrae that connects the body to the posterior elements [23].

In this context, we choose to deal with long trans-isthmic (LS) and short isthmic screws (SS): short isthmic screws have the same trajectory as long trans-isthmic screws, but they stop short to the beginning of the isthmus, therefore consistently reducing the risk of vertebral artery injury. On the contrary, trans-isthmic screws are typically inserted in the pedicle of C2 across the isthmus.

The main result of the present study is that the pull-out strength of trans-isthmic screws was higher than for isthmic screws (60 % additional pull-out resistance for LS).

Although pure pull-out is not the typical mode of failure seen in clinical situations, pull-out testing is thought to be a good predictor of screw fixation strength and is considered as the standard biomechanical evaluation when the goal is to compare screw design or screw insertion technique [24]. Indeed, several studies have compared the axial pull-out strength of pedicle screws in the thoracic or lumbar spine [14, 20, 25–29]. Moreover, the standards concerning the screws testing methods recommend axial pull-out test [24]. On the other hand, even if there is a significant difference between two types of screw during pull-out testing, the 3D comportment is unknown. In fact, in a 3D biomechanical analysis, Sim et al. [13] have not shown significant difference between isthmic and trans-isthmic screws incorporated in a Harms C1–C2 osteosynthesis.

Conclusion

On the basis of our study, we found that the pull-out strength of trans-isthmic screws was significantly higher (60 % additional pull-out resistance for LS) than short isthmic screws. Based on these results, long pedicle screws as described by Harms remain the gold standard of screw–rod fixations. Although associated with an inferior resistance, short isthmic screws may be used in case of narrow isthmus which contraindicates 3.5-mm screw insertion, and done so in order to limit the vascular risk. However, short isthmus screw should not be considered as the first option for C2 instrumentation. The influence of bone quality is unclear in our study, but short isthmus screw should be considered with caution in case of poor bone quality.

Further testing including fatigue and full upper cervical spine segment loading would allow complementing our results by comparing the stability provided by both screw options within more physiological loadings.

Compliance with ethical standards

Conflict of interest All authors declare that they have no conflict of interest.

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